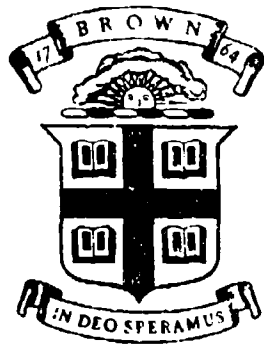


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for Three Different Tempers of 4340 VAR Steel.

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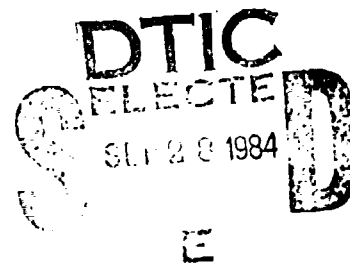
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to study history effects in these three tempers. For this purpose a prestrain was imposed at one temperature and strain rate, followed by continued straining at a new temperature or at a new strain rate.

Results provide stress-strain curves in shear for the three tempers of this steel. Temperature effects appear greater between -190°C and -50°C than between -50°C and room temperature, particularly for the 200°C temper, while the strain rate sensitivity is about the same as found in mild steel. History effects are quite small for the 600°C and 425°C tempers, even at large strains. However, for the 200°C temper a prestrain at -50°C followed by a temperature change to -190°C requires a higher flow stress than does deformation imposed entirely at the lower temperature. A comparison is made to history effects in other BCC metals.

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Strain Rate Effects and Temperature History Effects

for Three Different Tempers of 4340 VAR Steel

by

S. Tanimura* and J. Duffy**

ABSTRACT

A series of experiments is described in which specimens of AISI 4340 VAR steel are deformed in shear at temperatures ranging from -190°C to 200°C . The tests were performed in a torsional Kolsky bar at quasi-static and dynamic strain rates. Before testing all the specimens were normalized, austenitized and tempered either at 200°C , 425°C or 600°C , representing hardnesses of 55, 44, and 33, respectively, on the Rockwell C scale. In addition to constant temperature and constant strain rate tests, a number of experiments was performed to study history effects in these three tempers. For this purpose a prestrain was imposed at one temperature and strain rate, followed by continued straining at a new temperature or at a new strain rate.

Results provide stress-strain curves in shear for the three tempers of this steel. Temperature effects appear greater between -190°C and -50°C than between -50°C and room temperature, particularly for the 200°C temper, while the strain rate sensitivity is about the same as found in mild steel. History effects are quite small for the 600°C and 425°C tempers, even at large strains. However, for the 200°C temper a prestrain at -50°C followed by a temperature change to -190°C requires a higher flow stress than does deformation imposed entirely at the lower temperature. A comparison is made to history effects in other BCC metals.

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I Introduction

The stress-strain behavior of steels, and of other BCC metals, in the low temperature range differs in a number of respects from that of the FCC metals. It has been found, for instance, that strain rate sensitivity generally is greater for steels, while strain rate history and temperature history effects usually are not as pronounced, at least in the neighborhood of room temperature (1,2). One factor that influences strongly the behavior of steels is dynamic strain aging, which results in the familiar peak in the stress versus temperature curve usually occurring in the neighborhood of room temperature (3). The influence of strain rate on this peak is to shift its position to higher temperatures as strain rate is increased. Similarly, a plot of flow stress versus strain rate frequently shows a relative minimum rather than a monotonic increase with strain rate as in the FCC metals. History effects in BCC metals reveal a complex and as yet not well-understood behavior particularly at low temperatures and for some ranges of strain rates (4-10). Experimental evidence demonstrates that the influence of strain rate and temperature history on flow stress is far more complicated for steels than for aluminum or copper.

Due to its many applications, a particularly interesting steel is AISI 4340 alloy and, for the present investigation, round bars of this steel, processed by vacuum arc remelting (VAR), were obtained from Republic Steel Corporation. Since the mechanical properties of this steel are strongly sensitive to the choice of heat treatment, specimens were subjected to one of three different heat treatments to provide a representative range of properties. Both quasi-static and dynamic stress-strain curves in shear were then obtained by twisting short thin-walled tubular specimens in a torsional Kolsky bar (split-Hopkinson bar). These stress-strain curves covered the temperature range from -190°C to room temperature. In addition to tests at constant temperature and strain rate, a series of incremental temperature tests was performed, in some cases combined with increments in strain rate. The ultimate purpose of this work is to establish experimental data for derivation of a constitutive relation for this steel, preferably based on concepts of dislocation dynamics (11). An example of such a relation that includes strain rate and temperature effects as well as history effects is given by Tanimura (12).

II Apparatus and Specimens

1) Apparatus

All tests described in this report were performed using short thin-walled tubular specimens loaded in a torsional Kolsky bar (split-Hopkinson bar). With it one can perform dynamic or quasi-static tests over a broad temperature range by enclosing the specimen in an environmental chamber (13), the rate of flow of liquid nitrogen into the chamber setting the specimen's temperature to any value between 20°C and -190°C. As part of this investigation, incremental temperature tests were also performed. By adjusting the flow of liquid nitrogen into the chamber the specimen's temperature can be changed quickly from one value to a lower value: a drop in specimen temperature from 20°C to -190°C requires about one minute, as measured by a thermocouple 2 mm from the specimen and in contact with the Kolsky bar. This thermocouple is carefully insulated so it is not in contact with the atmosphere within the environmental chamber.

In some of the incremental temperature tests the temperature was changed in decrements of 70°C each from 20°C to -50°C, then to -120°C, and finally to -190°C, all within a small range of strains, so that the thermal effects on flow stress could be determined at a number of different temperatures. These multiple decrements in temperature performed on a single specimen eliminate the effects of variations in grain size, heat treatment, microstructure, inclusions and dimensions between test specimens. In addition, in a few tests a temperature increment was imposed by reheating the cold specimen while it was deforming quasi-statically. Reheating was effected using an electric heat gun; the temperature increment from -190°C to -50°C requires 8 minutes.

Although the torsional Kolsky bar has been fully described in previous publications (14,15), a brief summary of the technique is presented here. The dynamic strain rate in the torsional Kolsky bar is achieved by the sudden release of a stored torque at the end of the incident bar. This provides a torsional pulse that propagates down the incident bar to load the specimen in shear. In contrast, quasi-static loading is achieved by slowly twisting the further end of the transmitter bar while the incident bar is clamped to prevent rotation. In addition, the apparatus makes it possible to combine

static and dynamic loading to perform an incremental strain rate test in which the specimen is loaded first quasi-statically to a desired value of strain, whereupon the dynamic strain rate is superposed. The increment in strain rate from the quasi-static to the dynamic rate takes place in about 15 microseconds. In the case of quasi-static tests, the elastic response of the Kolsky bar between the rotary displacement transducers on either side of the specimen is subtracted from the recorded displacement to provide the net rotation between the ends of the specimen. The quasi-static strain rate for the present tests was $6 \times 10^{-4} \text{ s}^{-1}$ and the dynamic strain rate was in the range 400 s^{-1} to 600 s^{-1} .

2) Specimens

The specimens were all machined from round stock of AISI 4340 VAR (vacuum arc remelted) steel whose chemical composition is given in Table 1. Before machining, all specimens were normalized, austenitized and tempered at one of three temperatures 200°C , 425°C and 600°C . Since loading is imposed in torsion, the specimen is shaped as a thin-walled tube, with hexagonal flanges at each end to permit mounting in the Kolsky bar; dimensions are given in Figure 1. For the heat treatment, the specimens were placed in groups of six at the center of a 24-inch long tube-furnace. An argon atmosphere that first passed over copper chips was used to prevent oxidation during the heat treatment. The heat treating cycle, given in Table 2, consisted of three steps: (1) normalizing for 1/2 hour at 900°C , then cooling in argon; (2) austenitizing for 1/2 hour at 845°C , followed by an oil quench; (3) tempering for 1/2 hour. Specimens tempered at 425°C or at 600°C were oil quenched; specimens tempered at 200°C were cooled in argon. After the heat treatment, the specimens showed no visible signs of oxidation. Their hardness was measured as HRC 55, 44, 33 for the 200°C , 425°C and 600°C tempers, respectively. All specimens were cleaned inside and out and their dimensions measured carefully. If a specimen was found to have a taper along the gage length or a variation in wall thickness that was greater than 0.01 mm, it was rejected. For those tests designed to compare the flow stress characteristics of the same temper, the specimens were heat treated in one batch. This procedure had to be followed since it appears there are variations in stress levels due to minor variations in heat treatment between batches, occurring perhaps during the brief time necessary to drop the specimen in the quenching fluid.

Figure 2 shows photographs of the microstructures resulting from each of the three different tempers. The samples were taken from heat-treated specimens before mechanical testing. They were polished and given a nital etch which revealed a microstructure typical of tempered martensite, with randomly oriented lath packets. After testing, a check of carbon content in the thin-walled portion of two samples gave 0.41% and $0.42\% \pm 0.02\%$, thus providing no evidence of carbon depletion during the heat treatment. These percentages were determined by a combustion analysis with a LECO carbon determinator.

III Results and Discussion

The test results are presented primarily by means of graphs showing the stress-strain curves obtained under the different test conditions. These are summarized in Table 3, which groups the specimens in batches according to the heat-treatment, gives specimen numbers and a very brief description of the test performed. Since a fairly large variety of different tests was performed, it is necessary for the sake of clarity to group the results according to the type of test. A convenient grouping is as follows.

1) Tests at a constant quasi-static strain rate and constant temperature.

The stress-strain curves obtained for deformation at a constant strain rate are shown in Figures 3a to 3c. In all these tests the imposed strain rate was $6 \times 10^{-4} \text{ s}^{-1}$ in shear and deformation was carried to fracture. For each heat-treatment, the tests were performed at four different temperatures ranging from room temperature down to -190°C . In comparing these curves, the most obvious result is perhaps the pronounced influence of the heat-treatment. With a temper of 200°C the flow stress is about twice as great as found with a 600°C temper. As mentioned previously, this sensitivity to the heat treatment imposes the need for great care in the experimental procedure if the mechanical properties are not to vary from specimen to specimen. In particular, if the stress levels between different specimens are to be compared with one another and if any accuracy is to be achieved, then it is necessary that the specimens be heat-treated simultaneously and remain in close contact with one another during the heat-treatment. This procedure was followed in the present investigations. The results in Figures 3a to 3c also show that the heat treatment influences the strain at which the specimen finally fractures. In general, the fracture strain is quite low for the 200°C temper, while strains greater than 100% are attained with the 600°C temper. However, the experiments show considerable variation in the values of fracture strain, probably due to small variations in the specimens' wall-thicknesses combined with a low work-hardening rate. In addition to the above, the stress-strain curves show that the mechanical properties of this steel are fairly sensitive to test temperature, irrespective of the temper. The one exception to this statement comes for the 200°C temper, Figure 3c, where the flow stress is about the same at room temperature as at -50°C . This may be due to a more pronounced dynamic strain aging effect in the 200°C temper.

Table 4 compares the flow stress levels found in the present quasi-static tests with the results of other investigations on 4340 steels (17-19). Since the other tests were performed in tension, the present shear stress and strain values were converted to axial values using the Mises flow rule and incompressibility of plastic deformation. A precise comparison can not be expected since only Hickey and Anctil (17) tested a VAR steel and since, even for this steel, there are invariably differences from billet to billet as well as differences in the heat-treatment. Nevertheless, it appears that the present quasi-static results for all three tempers are in fairly close agreement with the results of others.

2) Tests at a Quasi-Static Strain Rate with an Increment in Temperature between -50°C and -190°C

The stress-strain behavior resulting from a sudden change in temperature during quasi-static deformation is shown in Figures 4a and 4b for the 600°C and the 200°C tempers, respectively. For the former, it appears that the effect of a prior deformation at one temperature followed by continued deformation at a different temperature is not very great. Indeed, if the drop in temperature from -50°C to -190°C occurs at a strain of about 4% (Specimen VT-228), then the temperature history effect is almost imperceptible, cf. the stress levels at -190°C in specimens VT-228 and VT-233. When the change occurs after 40% strain has accumulated (Specimen VT-231), then some history effect appears: initially the subsequent flow stress is somewhat lower than for deformation entirely at -190°C, and the work-hardening rate is somewhat greater. However, neither of these effects is pronounced. It should be pointed out here that, while it takes about one minute to change the temperature from -50°C to -190°C, the new flow stress level is not established until after about 3 minutes have expired. In other words, the specimen is at the new temperature long before the new flow stress level is established, so that any difference in the stress level can be attributed to a history effect rather than to any lag in the temperature change. When a temperature rise is imposed from -190°C to -50°C at 40% strain (Specimen VT-228 in Figure 4a), then history effects again are very small. There appears to be no difference in the initial flow stress after the temperature rise, but the work-hardening rate seems to change somewhat at the 40% strain when comparing Specimen VT-231 with VT-228. Results indicate also that the flow stress after the temperature

rise remains substantially constant from a strain of 40% to about 100%. In contrast, for a specimen deformed entirely at -50°C , the stress in this range does increase although the work-hardening rate is low (Specimen VT-66 in Figure 3a).

The behavior of the 200°C temper steel subjected to a rapid drop in temperature during deformation is quite different from that of the 600°C temper. As may be seen in Figure 4b, a prestrain at -50°C results in a higher flow stress at -190°C (Specimen VT-305) as compared with the flow stress in a specimen deformed entirely at -190°C (Specimen VT-304). While an overshoot of this type does not occur in the other two tempers, it has been observed in previous investigations with steels and other BCC metals. For instance, it was seen by Lindley (9) in experiments with a low carbon steel when its temperature was reduced during deformation from room temperature to -120°C . The overshoot occurred whether the change in temperature was imposed at 5, 10, 15 or 20 percent strain. A similar result was seen by Hartley and Duffy (5) with a 1020 hot-rolled steel when its temperature was reduced to -190°C . The reasons for the overshoot are not clear. By metallographic examination Lindley showed that the prestrain at room temperature inhibits twinning during the subsequent deformation at -120°C , whereas prestrain at -120°C does not, or at least does so only to a far lesser extent. Hartley and Duffy, on the other hand, did not observe twins. Another possible explanation might involve differences in dislocation multiplication rates at different temperatures and, as will be seen subsequently, at different strain rates. Perhaps the most likely explanation was proposed by Smith (10). He found that a prestrain at 7.5 s^{-1} results in a lower subsequent flow stress than a quasi-static prestrain, and suggested that there may be a larger density of mobile dislocations upon reloading due to the greater number of dislocation sources generated at the higher rate. As mentioned previously, a more pronounced dynamic strain aging effect in the 200°C temper deformed at room temperature appears to raise its flow stress so it is near the -50°C curve, Figure 3c. This same effect might explain the sharper yield point obtained with this temper after a temperature decrement, Figure 5c, than with the other tempers. Furthermore, if strain aging is larger at -50°C than at -190°C , then a decrement in temperature at -50°C would lead to the appearance of an overshoot.

3) Tests at a Quasi-Static Strain Rate with Multiple Increments in Temperature.

For a number of specimens the test temperature during quasi-static deformation was changed from room temperature to -190°C in three successive steps, each of -70°C . The reason for performing tests with multiple drops in temperature is to establish the variation of flow stress with test temperature. By employing a single specimen one avoids variations in properties between specimens. The dotted line in Figure 5a shows the stress-strain behavior of a 600°C temper specimen (VT-220) subjected to multiple drops in temperature just after initial yield: the test temperature was changed in rapid succession from room temperature to -50°C , from -50°C to -120°C and finally from -120°C to -190°C . Since it was desired to impose the multiple increments at approximately constant strain, the deformation process was halted whenever the specimen's temperature was decreased. Simultaneously, a small drop in load was imposed, as shown by the stress history in the figure. Once the new temperature was established, which took about one minute, twisting of the end of the bar was resumed at the same rate as before. As a result, the stress increased at approximately constant strain until renewed yielding was observed; this process took about two minutes from the start of reloading. As soon as renewed yielding was established, then the next temperature drop was imposed. As may be seen from Figure 5a, in the case of specimen VT-220 the sequence of three consecutive drops in temperature was carried out at a very low strain. For specimen VT-221 a strain of about 40% was imposed at room temperature before the first drop in temperature was imposed. In addition, deformation in this specimen was stopped at about 60% strain and the stress allowed to drop back to a value approximately equal to that of the flow stress in a specimen deformed to the same strain entirely at room temperature. This unloading and reloading took about seven minutes. The brief drop in load does not seem to influence the subsequent stress-strain behavior except for the generation of some serrations.

Similar multiple drops in temperature were imposed on specimens of the 425°C and 200°C tempers, Figures 5b and 5c. It is evident that preloading at room temperature to 40% strain gives evidence of some history effect. In the case of the 200°C temper, Figure 5c, there appears again to be an overshoot for multiple drops in temperature as there was for a single drop in temperature, Figure 4b. In this case there is also some evidence of a small upper and lower yield point on each reloading.

In order to draw conclusions from the multiple temperature drop tests it is useful to plot flow stress as a function of temperature, Figure 6. In the case of the 200°C temper, for example, repeated temperature drops were imposed on specimen VT-301, Figure 5c, at a strain of about 2%. Figure 6 shows the flow stress at 2% strain in this specimen at room temperature and the subsequent yield stresses at each of the lower temperatures. The best curve drawn through the experimental points is close to a straight line, except perhaps in the neighborhood of room temperature. If, for the 200°C temper the multiple drops in temperature are imposed at a strain of 12%, specimen VT-302, it can be expected that the values of the stress will be somewhat greater, and this is indeed the case. It is significant, however, that the two curves, VT-301 and VT-302, are nearly parallel. A discussion of this result is presented below. Since for specimen VT-302 upper and lower yield points were obtained, both results are shown in the figure: the stress at the lower yield point is represented by small circles, while for the upper yield point a very short dotted line is used. Figure 6 also shows the results of the multiple temperature drop tests for the 425°C and 600°C tempers. These two tempers produce a more ductile steel, making it possible to impose successive temperature drops at a greater strain (40%). The curves in Figure 6, giving the flow stress of the 4340 VAR steel, are all nearly parallel for the three heat treatments and over the strain range considered. Furthermore, the curves are almost straight lines at least in the range -190°C to -50°C. This means that the effect of temperature is the same for the three heat treatments up to fairly large strains. From -50°C to room temperature there is some departure from a linear relation due probably to strain aging effects. For purposes of comparison, experiments were conducted with two plain carbon steels, as well as with an aluminum, and their respective values of flow stress are plotted in the same figure.

4) Incremental Strain Rate Tests

A number of tests were performed in which an initial deformation was imposed at a quasi-static rate ($6 \times 10^{-4} \text{ s}^{-1}$) followed by a sudden increase in strain rate to about 400 s^{-1} . The torsional Kolsky bar is ideally suited for this type of test. Quasi-static deformation can be continued to any desired value of strain and the change in strain rate occurs quite rapidly (about 15 microseconds) and with no significant unloading of the specimen. Furthermore,

during the dynamic portion of the test the output of the transmitter gages, Figure 7, gives a direct measure of the stress increment rather than giving the total stress, thus avoiding errors due to small differences between large numbers. In the oscillogram shown in Figure 7, for VT-314, τ_s represents the stress just before the increment in strain rate is imposed. Hence τ_s is the maximum quasi-static stress, which equals about 1075 MPa for specimen VT-314. At the instant designated by t_s in the figure the stress starts to increase rapidly due to the change in strain rate, and the vertical coordinate gives a measure of the subsequent increase in stress above the τ_s value. These results can be replotted to give the increment in stress as a function of strain, as shown in Figure 8, where the origin represents the values of τ_s and γ_s , and the coordinates give the subsequent change in stress and strain. The origin for this test (Specimen VT-314) is at $\tau_s=1075$ MPa and $\gamma_s=0.5\%$. The initial increment in stress is about 100 MPa and subsequent work-hardening results in a stress of about 225 MPa above the value of τ_s , i.e. a total of 1300 MPa. The complete stress-strain curve is shown as the solid line in Figure 9. Judging from the two tests shown in this figure it would appear that, at room temperature, the 200°C temper is not particularly sensitive to strain rate. Although not evident from the figure, the initial stress level for the two curves shown is approximately the same. At 0.5% strain the stress for specimen VT-314 increases suddenly due to the imposed strain rate increment which gives evidence of a positive strain rate sensitivity. However, the stress in the quasi-static test (VT-315) also increases showing a pronounced work-hardening rate. Hence, for different reasons the quasi-static and dynamic stress levels are nearly the same. The best conclusion one can draw is that, at room temperature, strain rate sensitivity for the 200°C temper is not great in the range from the quasi-static to 400 s⁻¹. A comparison with other steels is given below.

Two examples of incremental strain rate tests conducted for the 425°C temper, are given in Figure 10. In each test, quasi-static deformation was carried to about 3% strain at which point a small amount of unloading was imposed followed by the strain rate increment. As may be seen, fracture in both specimens occurred at a low value of strain. The results show a positive but modest strain rate sensitivity, comparable with that found in mild steel.

Figure 11 shows the results of a series of incremental strain rate tests with specimens of the 600°C temper. In some of these tests the increment in strain rate was imposed following a decrement in temperature. In all four tests the quasi-static prestrain was carried to 40% before the temperature was changed.

A summary of the results obtained in the incremental strain rate tests is presented in Figure 12, and Table 5. The stress values plotted in the figure represent the flow stress either immediately before or immediately after the strain rate increment. The former are plotted as a point and the latter as a point placed within a capital letter D. Dotted lines are used to connect static flow stress values found in testing specimens heat-treated within the same batch, and solid lines for the stress immediately following the increment in strain rate. Values of the strain at which the rate increment was imposed are also presented. For the 200°C temper they are specified for each specimen with the specimen number. For the 425°C temper all increments were imposed at 3% strain, while for the 600°C temper the lower pair of curves (VT-222 and VT-226) represents an increment at 2% strain and the higher pair at 40% strain (VT-234, 237, 238 and 239).

Based on the results shown in Figure 12, values of strain rate sensitivity and an activation volume have been calculated as detailed below, and are shown in Table 5, in which the grouping is by heat-treatment batch. In this table, γ_s refers to the value of the strain at which the increment in strain rate is imposed to raise the strain rate from $\dot{\gamma}_s$ to $\dot{\gamma}_d$, while the stress jumps from τ_s to τ_d . Two measures of strain rate sensitivity frequently used are defined by

$$m_t = \frac{\ln \tau_d / \tau_s}{\ln \dot{\gamma}_d / \dot{\gamma}_s} \quad \text{and} \quad 1/\beta_t = \frac{\tau_d - \tau_s}{\ln \dot{\gamma}_d / \dot{\gamma}_s}$$

where the subscript t designates a "true" strain rate sensitivity, i.e. one based on results of incremental tests, rather than the more usual "apparent" strain rate sensitivity which is found by comparing results of two tests at different but constant strain rates. For FCC and HCP metals values of apparent strain rate sensitivity are greater than true values because of

history effects (16). In contrast, for BCC metals the two tend to be almost equal since history effects are small. This is the case in the present tests, except for the 200°C temper for which the overshoot makes the true strain rate sensitivity exceed the apparent. A similar overshoot with iron or mild steel had been seen by Harding (8), by Eleiche and Campbell (20) and by Klepaczko and Duffy (4). Present results are consistent in that the effect is limited to low temperatures or at least is most pronounced at low temperatures. Campbell and Briggs (7) observed an overshoot with two other BCC metals: molybdenum and niobium. All their tests were conducted at room temperature but the overshoot appeared to be limited to an intermediate range of strain rates (0.5 to 5 s⁻¹). Thus the behavior of BCC metals is complicated and it is not surprising that an overshoot can occur with a particular temper of 4340 steel.

The numerical values of strain rate sensitivities listed in Table 5 are close to those found in tests with mild steel (20). In the case of the 600°C temper, for which more tests were conducted and for which the strain rate increment was imposed always at the same strain, there appears to be a peak in the strain rate sensitivity at about 153°K, i.e. at $T/T_m = 0.085$. A similar peak, occurring at about the same temperature, has been observed by a number of other investigators, albeit in tests limited to lower strain rates (22). In this respect, the trend shown in the strain rate sensitivities of the 200°C temper again appears to indicate an anomalous behavior.

Values of activation volume v^* were calculated using

$$v^* \approx - \left(\frac{\partial G}{\partial \tau} \right)_T = \beta_t kT$$

where k is Boltzmann's constant and T is the temperature in degrees absolute. Use of this equation presumes that the deformation mechanism is thermally activated and that the change in activation free energy ΔG necessary to overcome the barriers to flow is a linear function of applied stress. In Table 5 these values are presented in non-dimensional form by dividing v^* by b^3 , where b , the Burgers vector, is equal to 2.49 Å. Figure 13 compares present values for the 600°C temper with those obtained by other investigators

for a variety of steels and iron, as presented by Conrad (21), but derived from tests at lower strain rates. The values of activation volume are given as a function of the thermal stress component $\tau^* = \tau - \tau_u$, where τ is the applied shear stress and τ_u its athermal component. In plotting this figure, Conrad took τ_u as equal to the applied stress at $T = 300^\circ\text{K}$. For the present tests and the 600°C temper at 40% strain this makes $\tau_u = 628 \text{ MPa}$. As may be seen in Figure 13, agreement between the two curves is quite good.

The temperature dependence of the values of v^*/b^3 agrees quite closely with that of Eleiche and Campbell in tests with a mild steel (0.125% carbon) at strain rates comparable to those presented here (20). They found, for instance, that v^*/b^3 decreased from 50 to 20 to 10 as test temperature went from 300°K to 200°K to 130°K . The values of v^*/b^3 all lie within a range for which the dominant deformation mechanism is overcoming the Peierls-Narbarro stress (22,23).

IV Conclusions

Experiments were performed to determine the quasi-static and dynamic stress-strain behavior in shear of specimens of AISI 4340 VAR steel, tempered to hardnesses of 55, 44 and 33 on the Rockwell C scale. For this purpose short tubular specimens were loaded in a torsional Kolsky bar at strain rates in shear of $6 \times 10^{-4} \text{ s}^{-1}$ and 400 s^{-1} and over the temperature range -190°C to room temperature. In addition, temperature history effects were examined by deforming the specimen first at one temperature up to a given value of strain, and then imposing a rapid decrement or increment in temperature and allowing deformation to continue to fracture. A few specimens were also subjected to multiple increments in temperature during deformation. Similarly, incremental strain rate experiments were conducted in which the strain rate was increased rapidly from the quasi-static to the dynamic rate.

Only the results of the quasi-static tests at room temperature can be compared with those of other investigators and these show close agreement. As expected these results show that the flow stress level in 4340 VAR steel depends quite strongly on the temper, increasing from about 520 MPa for the 600°C temper to 760 MPa for the 425°C temper to 1140 MPa for the 200°C temper. The change in flow stress with test temperature, in the range -190°C to -50°C is about the same for all three tempers even up to large strains. Furthermore, for this range of temperatures it appears that flow stress decreases linearly with an increase in temperature. However, the rate of change is smaller in the range -50°C to 20°C , particularly for the 200°C temper. This is probably due to the effects of dynamic strain aging and is in agreement with the general trend seen by Manjoine for plain carbon steels (3).

Strain rate sensitivity for all three tempers of the 4340 VAR steel is about the same as found in mild steel and considerably greater than that seen in aluminum or other FCC metals (2). For the 425°C and 600°C tempers it is nearly independent of test temperature in the range -190°C to room temperature, although there is a small relative maximum at about -120°C . For the 200°C temper, the strain rate sensitivity is considerably greater at -190°C than at room temperature. Based on these results, an activation volume was calculated and, for the 600°C temper, its value was found to agree closely with the results of other experiments on iron and steels. For an

increase in applied stress, the numerical values of activation volume were found to decrease from about $50 b^3$ to about $10 b^3$, where b is the Burgers vector. According to Conrad this indicates that the dominant deformation mechanism is overcoming the Peierls-Nabarro stress (22).

The effects of temperature history and strain rate history on the subsequent flow stress are complicated, but at the same time are characteristic of BCC metals. For the 200°C temper the effects of a prior deformation are pronounced, whereas they are small for the other two tempers. For the 600°C temper, for instance, history effects at a 5% strain are within the range of experimental error. Even at large strains (40%) the effect is small; there is evidence, however, that the flow stress at -190°C is somewhat lower after preloading at a higher temperature. There is also some evidence that the work-hardening rate may be slightly lower following an increase in temperature from -190°C to -50°C during deformation. It is clear, however, that the 200°C temper does not behave in the same way as the other two tempers. For instance, for this temper, a sudden drop in temperature from -50°C to -190°C raises the flow stress to a value that exceeds considerably that found in a like specimen deformed entirely at -190°C. An overshoot of this nature is quite characteristic of deformation in BCC metals, and generally is limited to certain temperature and strain rate ranges.

The fact that the experiments described included increments in both temperature and strain rate, in addition to the more conventional tests under constant temperature and strain rate conditions, should make it possible to develop uniaxial constitutive equations for different hardnesses of AISI 4340 VAR steel that include temperature, strain rate and their history.

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TABLE 1

Chemical Composition of 4340 VAR Steel
 Data from Republic Steel: Heat No. 3841687
 (Wt. % of 4340 Steel Alloy)

<u>C</u>	<u>Mn</u>	<u>P</u>	<u>S</u>	<u>Si</u>	<u>Cu</u>	<u>Ni</u>	<u>Cr</u>	<u>Mo</u>	<u>Al</u>	<u>N</u>	<u>O</u>	<u>H ppm</u>
.42	.46	.009	.001	.28	.19	1.74	.89	.21	.031	.005	.001	1.0

TABLE 2

Heat Treatments

	Temperature °C	Time (Hours)	Cooling
Normalize	900	1/2	Argon Cool
Austenitize	845	1/2	Oil Quench
Temper	600	1/2	Oil Quench
	425	1/2	Oil Quench
	200	1/2	Argon Cool

TABLE 3

List of Tests Performed

Specimen Numbers Arranged by Batch	Temper °C	Test Description	Strain Rate (s ⁻¹)
VT-19	425	Dynamic Jump at $\gamma = 3\%$	450 ~ 600
VT-20		Dynamic Jump at $\gamma = 3\%$	400 ~ 500
VT-21		Double Jump at $\gamma = 3\%$	450 ~ 600
VT-63, VT-65, VT-66, VT-67	600	Static	6×10^{-4}
VT-107, VT-108 VT-109, VT-110	425	Static	6×10^{-4}
VT-115, VT-116 VT-118	425	Static, Temperature Jump	6×10^{-4}
VT-220, VT-221	600	Static, Temperature Jump	6×10^{-4}
VT-222	600	Dynamic Jump at $\gamma = 2\%$	500 ~ 650
VT-226		Dynamic Jump at $\gamma = 2\%$	500 ~ 650
VT-228, VT-231, VT-223	600	Static, Temperature Jump	6×10^{-4}
VT-234	600	Dynamic Jump at $\gamma = 40\%$	1450 ~ 1550
VT-237		Double Jump at $\gamma = 40\%$	400 ~ 600
VT-238		Double Jump at $\gamma = 40\%$	400 ~ 500
VT-239		Double Jump at $\gamma = 40\%$	400 ~ 500
VT-301, VT-302, VT-304, VT-305	200	Static, Temperature Jump	6×10^{-4}
VT-313	200	Static, Temperature Jump	6×10^{-4}
VT-314		Dynamic Jump at $\gamma = 0.5\%$	400
VT-315		Static	6×10^{-4}
VT-318		Dynamic Jump at $\gamma = 4\%$	400
VT-319	200	Dynamic Jump at $\gamma = 2\%$	400 ~ 500
VT-320		Dynamic Jump at $\gamma = 3\%$	400 ~ 500
VT-324		Double Jump at $\gamma = 11\%$	200 ~ 350
VT-325, VT-326 VT-327, VT-330	200	Static	6×10^{-4}

TABLE 4

Quasi-Static Experiments:
Comparison with Results of Other Investigators

Investigators- Steel (Mode of Loading)	(Heat Treatment) & Temper	Rockwell Hardness R _C	Initial Yield Stress c _y (MPa)	Ultimate Tensile Strength σ _{uts} (MPa)
Hickey-	(900C 1 Hr AC			
Anctil (17)	845C 1 Hr OQ)			
4340 VAR	204C	54	1610	2000
(Tension)	427C	44	1350	1480
	649C	31	840	980
Chait (18)	(845C ½ Hr OQ)			
4340	204C 2 Hr AC	51	1860	2340*
(Tension)	427C 2 Hr AC	44	1410	1580*
	538C 2 Hr AC	38	1170	1450*
Present	(900C ½ Hr AC			
Results	845C ½ Hr OQ)			
4340 VAR	200C ½ Hr AC	55	1860**	2200**
(Torsion)	425C ½ Hr OQ	44	1290**	1510**
	600C ½ Hr OQ	33	850**	1170**

*Stress values converted by Chait to account for necking.

**Equivalent stress values were obtained from torsional results

using $\sigma = \tau\sqrt{3}$; $\epsilon = \gamma/\sqrt{3}$

TABLE 5

Calculation of Strain Rate Sensitivity and Activation Volume

Temper (°C)	Specimen Number	Test Temperature (°K)	Data from Jump Tests					Strain Rate Sensitivity		Act. Vol.
			γ_s (%)	τ_d (MPa)	τ_s (MPa)	$\dot{\gamma}_d$ (s ⁻¹)	$\dot{\gamma}_s$ (s ⁻¹)	m_t	$1/\dot{\epsilon}_t$ (MPa)	
200	314	295	0.5	1159	1076	400	$6 \cdot 10^{-4}$	.0055	6.19	42.7
	318	83	4	1497	1339	400	$6 \cdot 10^{-4}$	.0083	11.78	6.3
200	320	295	3	1228	1139	450	$6 \cdot 10^{-4}$	.0056	6.58	39.8
	324	223	11	1366	1270	275	$6 \cdot 10^{-4}$	.0056	7.36	26.9
	319	83	2	1553	1401	450	$6 \cdot 10^{-4}$	.0076	11.23	6.6
425	19	295	3	828	759	525	$6 \cdot 10^{-4}$	.0064	5.04	52.3
	21	223	3	932	842	525	$6 \cdot 10^{-4}$	.0074	6.58	30.4
	20	83	3	1118	1035	450	$6 \cdot 10^{-4}$	.0057	6.13	12.1
600	234	295	40	697	628	1500	$6 \cdot 10^{-4}$	.0071	4.68	56.3
	237	223	40	780	676	500	$6 \cdot 10^{-4}$	.0105	7.63	26.3
	238	153	40	883	773	450	$6 \cdot 10^{-4}$	.0098	8.13	16.8
	239	83	40	973	869	450	$6 \cdot 10^{-4}$	.0098	7.69	9.7
600	222	295	2	600	524	575	$6 \cdot 10^{-4}$	.0098	5.52	47.9
	226	83	2	883	773	575	$6 \cdot 10^{-4}$	.0047	7.99	6.3

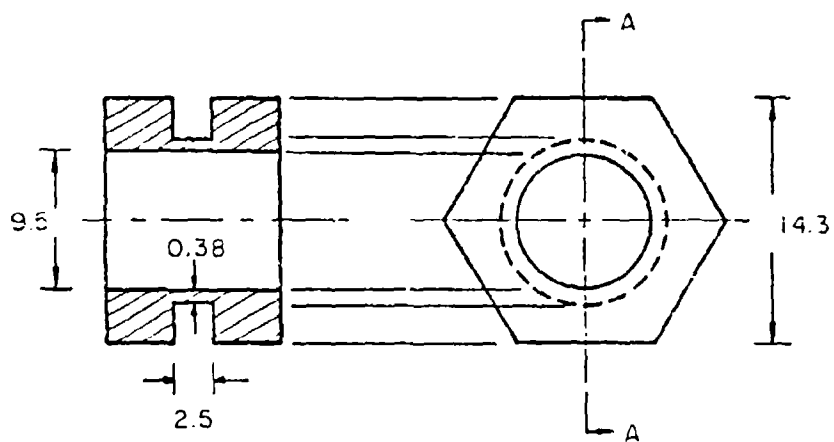
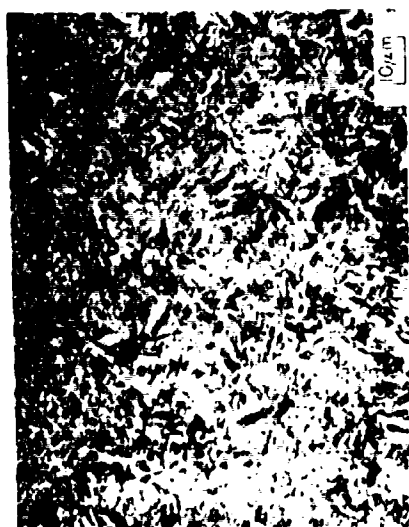
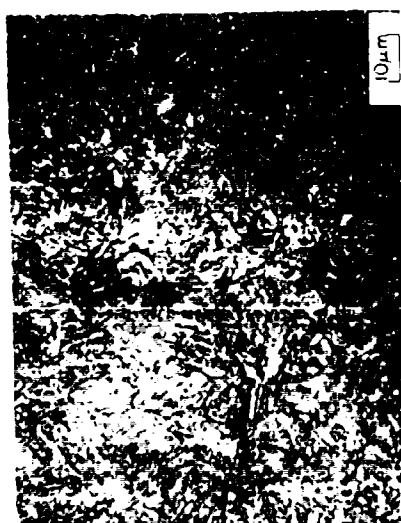


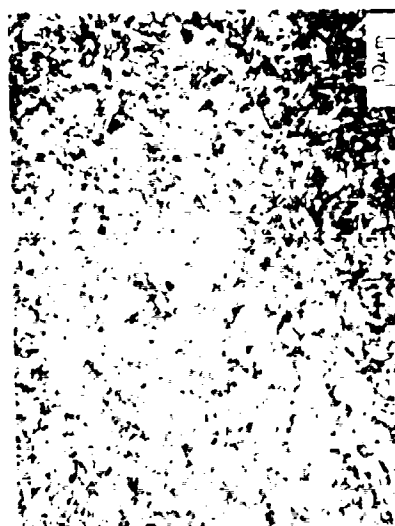
Figure 1 Details of Torsional Specimen with Hexagonal Mounting Flanges. Dimensions are in millimeters.



200°C TEMPER



425°C TEMPER



600°C TEMPER

FIGURE 2. MICROSTRUCTURES OF AISI 4340 VAR STEEL (UNDEFORMED METAL).

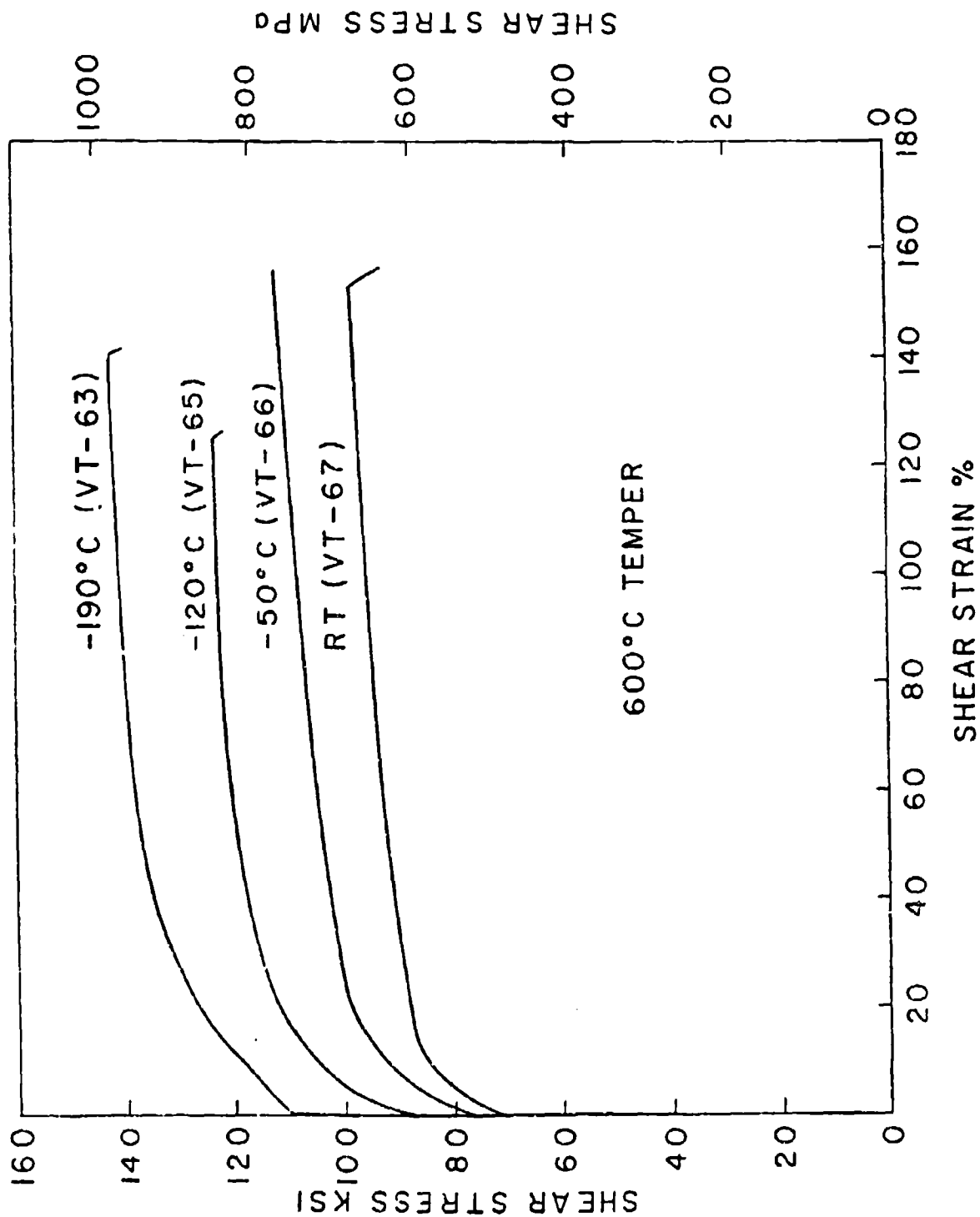


Figure 3a Results of Quasi-Static Tests, 600°C Temper.

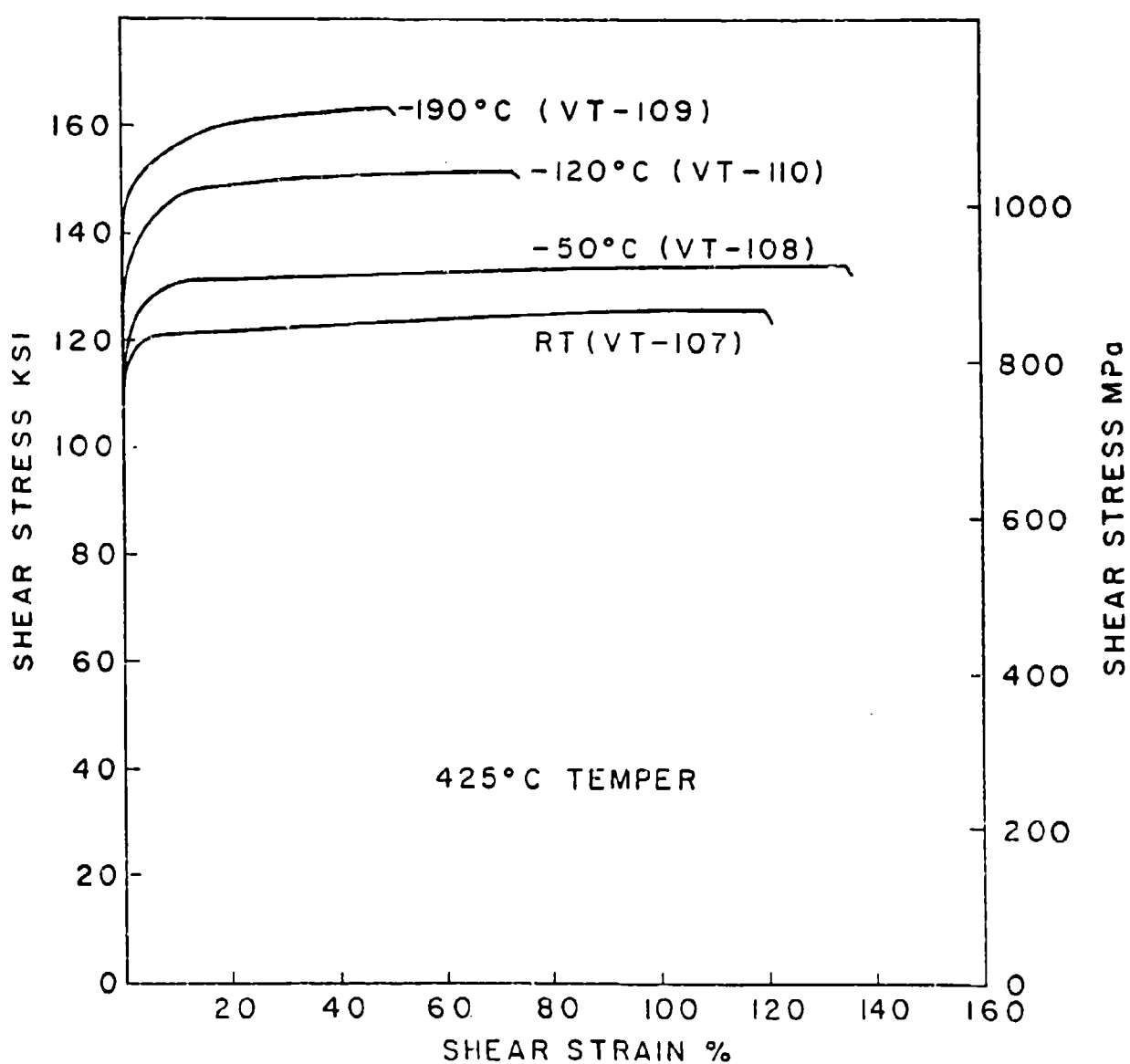


Figure 3b Results of Quasi-Static Tests, 425°C Temper.

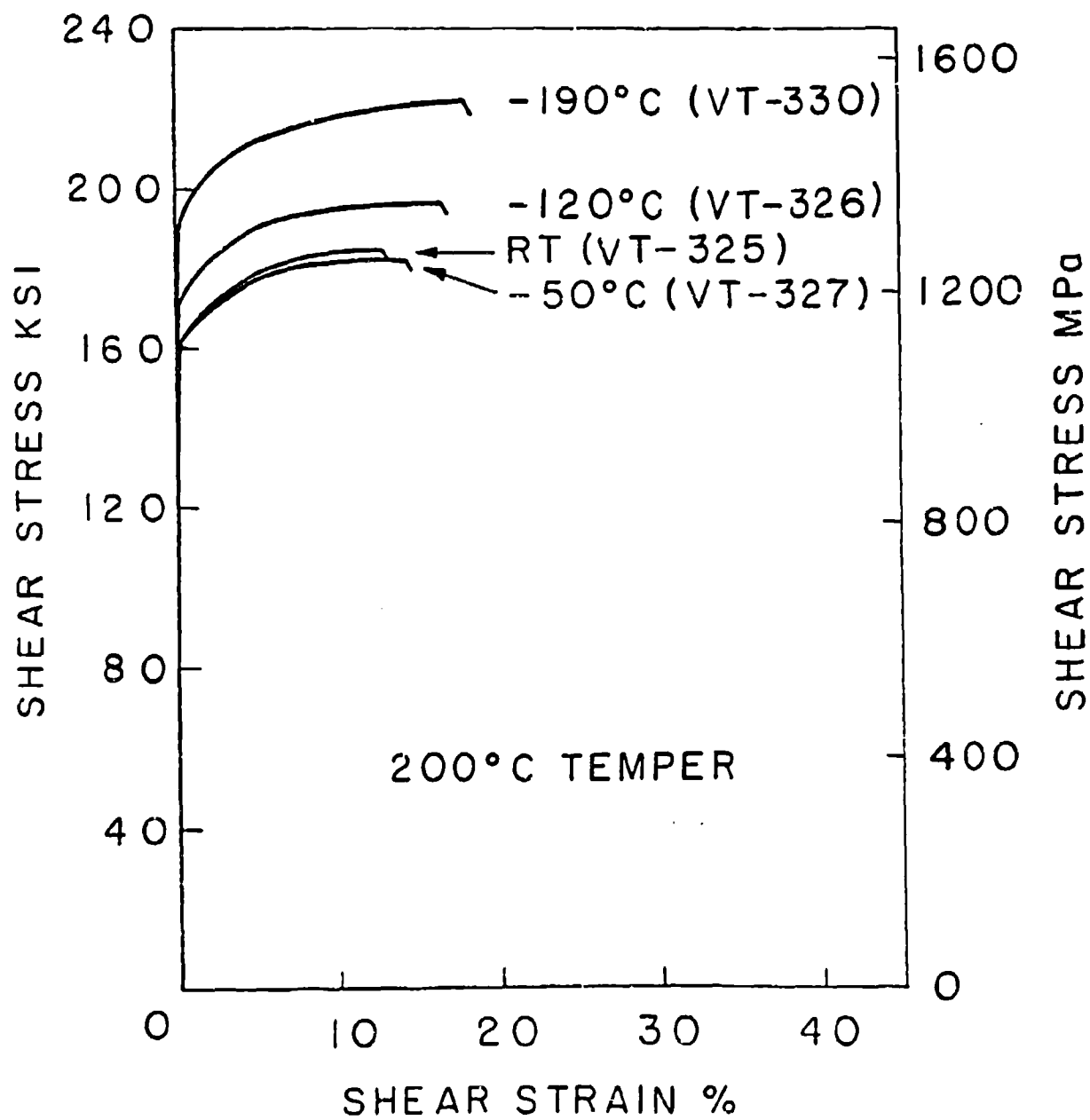


Figure 3c Results of Quasi-Static Tests 200°C Temper.

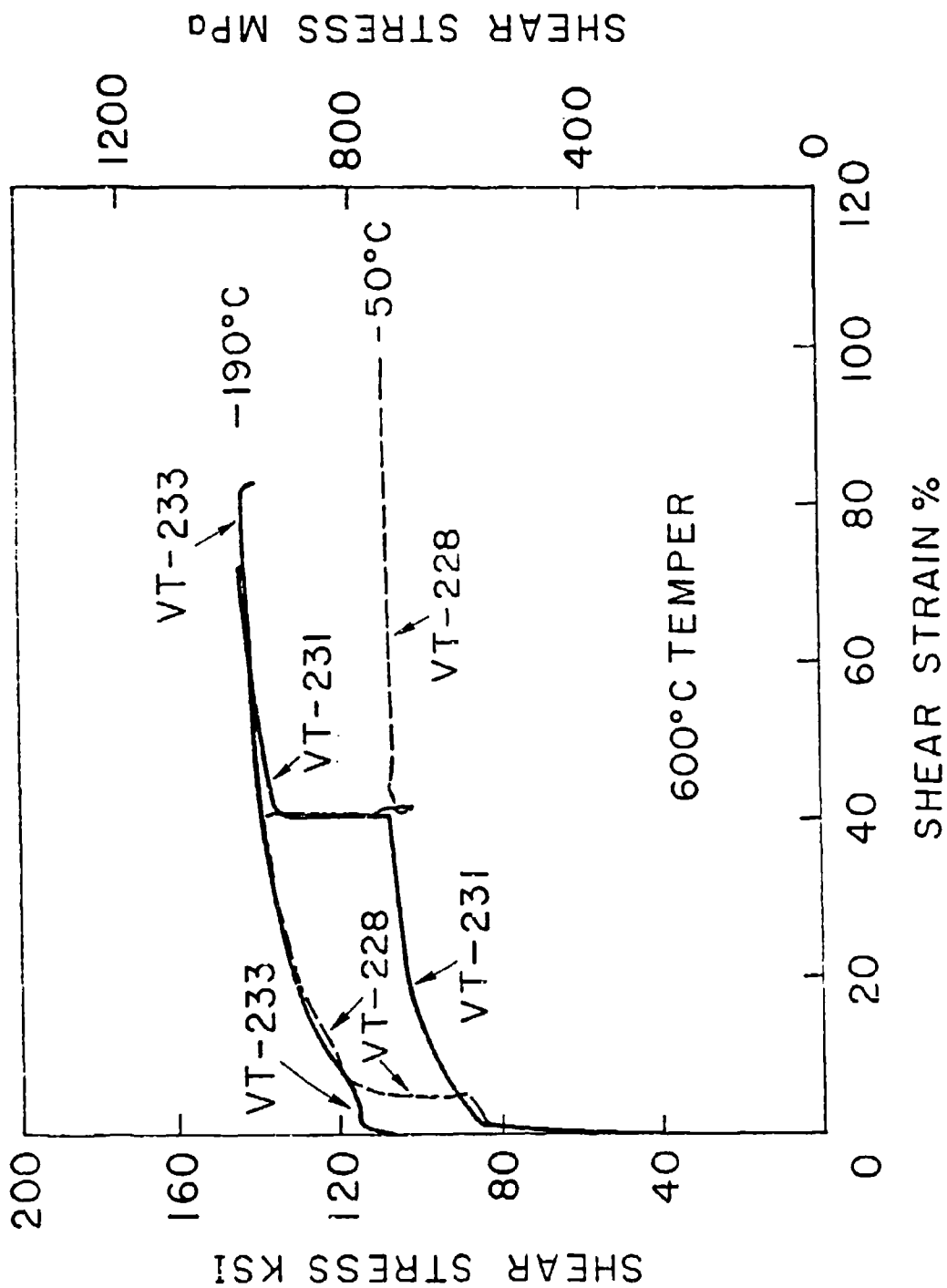


Figure 4a Incremental Temperature Tests at $\dot{\gamma} = 6 \times 10^{-4} \text{ s}^{-1}$, 600°C Temper.

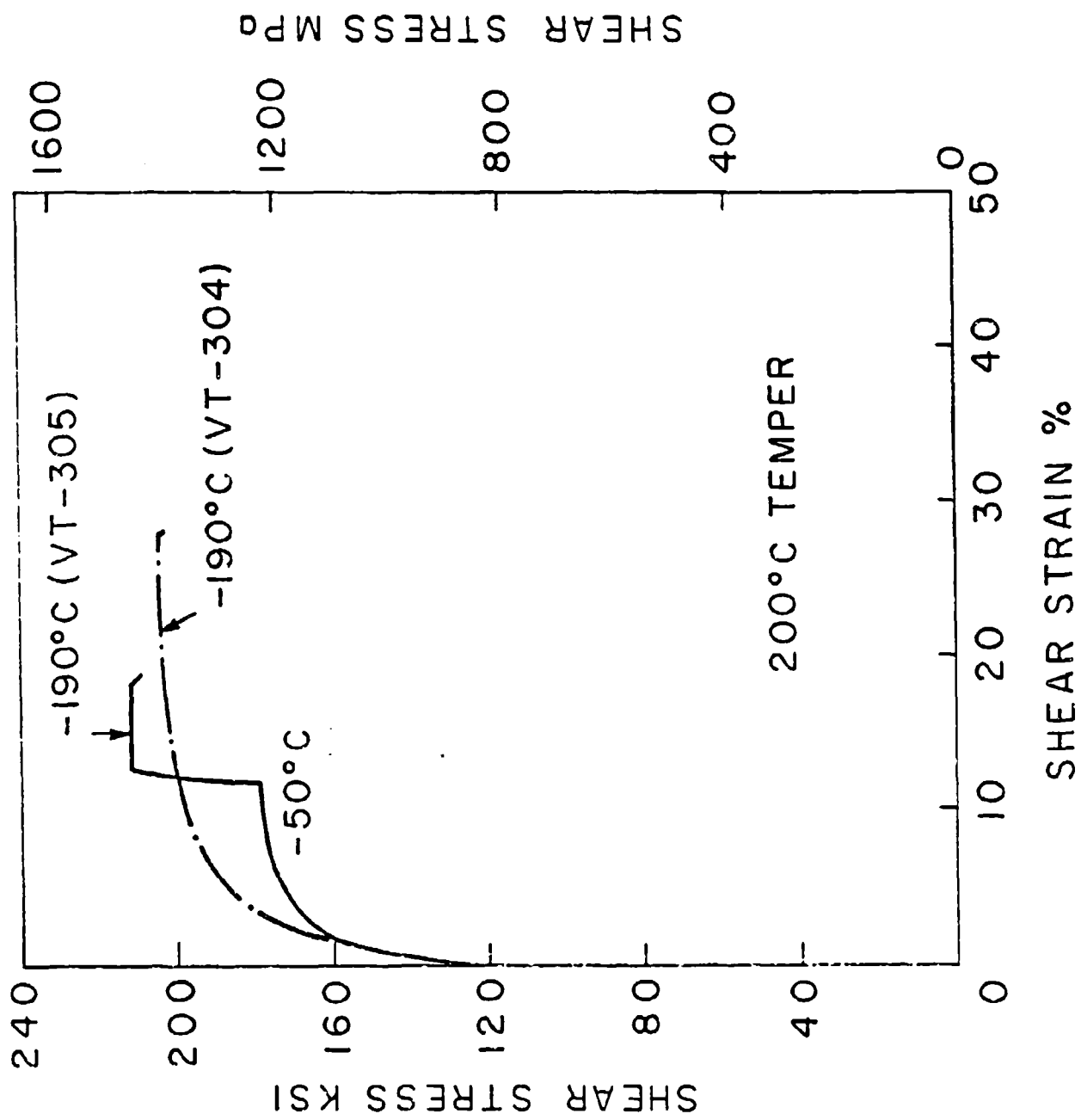


Figure 4b Incremental Temperature Tests at $\dot{\gamma} = 6 \times 10^{-4} \text{ s}^{-1}$, 200°C Temper.

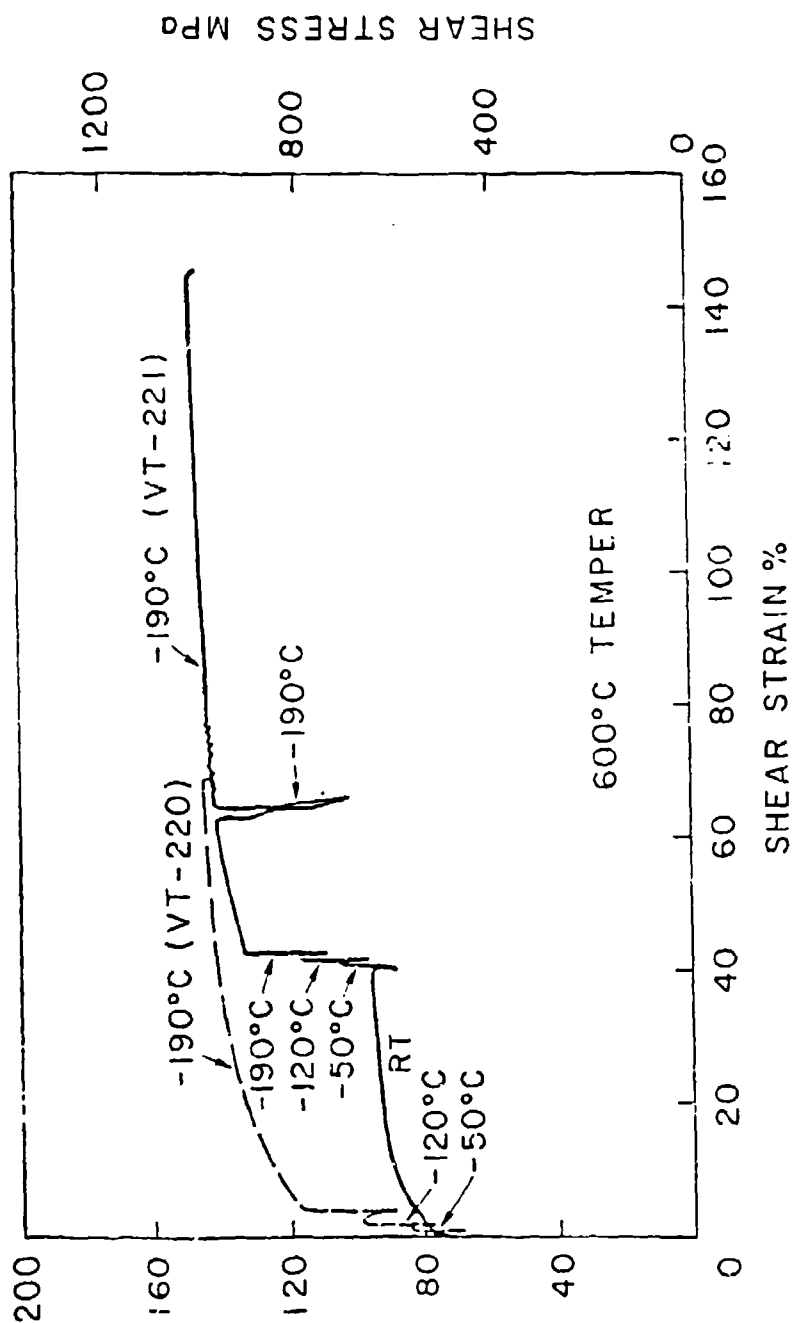


Figure 5a Multiple Incremental Temperature Tests at $\dot{\gamma} = 6 \times 10^{-4} \text{ s}^{-1}$, 600°C Temper.

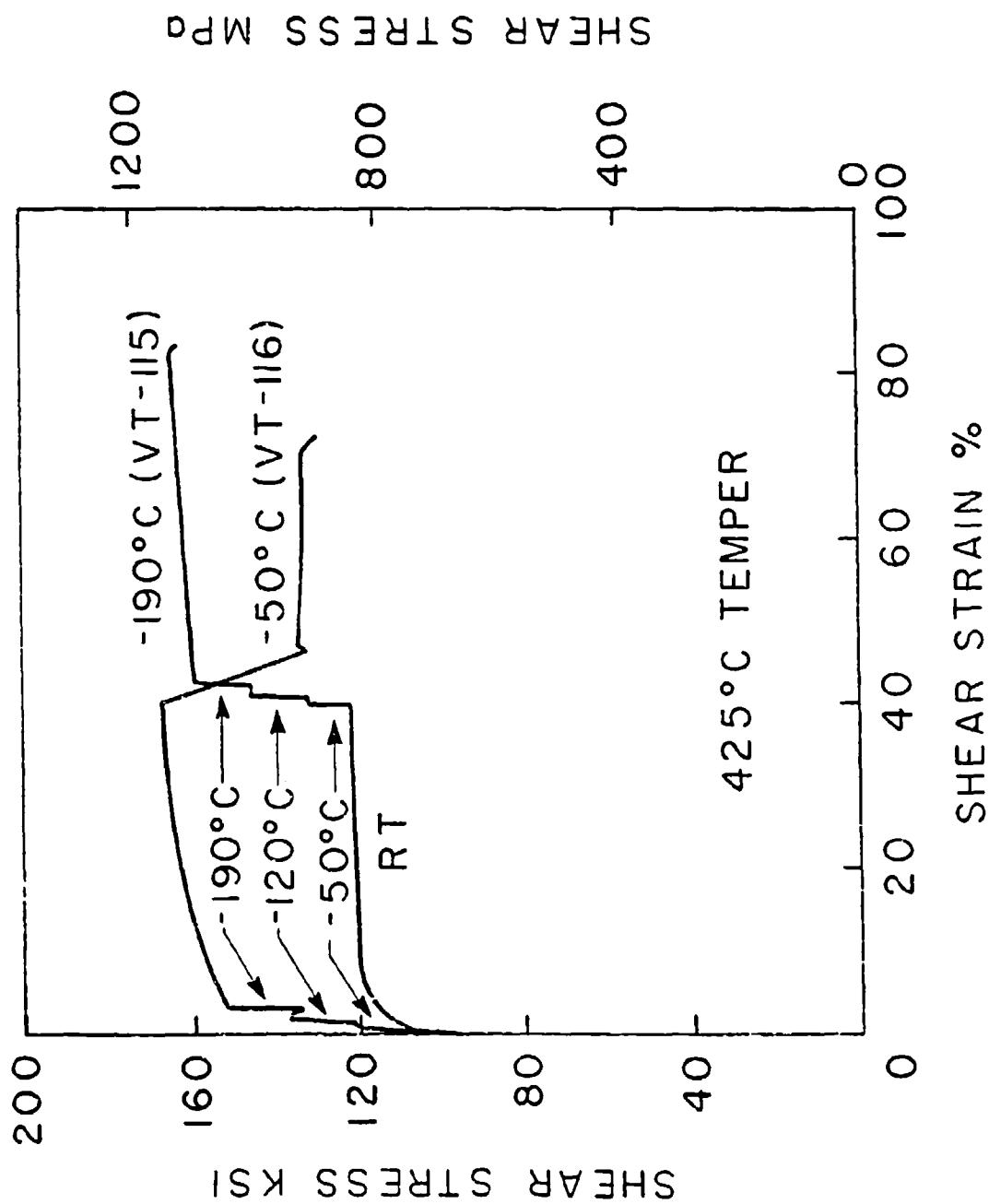


Figure 5b Multiple Incremental Temperature Tests at $\dot{\gamma} = 6 \times 10^{-4} \text{ s}^{-1}$, 425°C Temper.

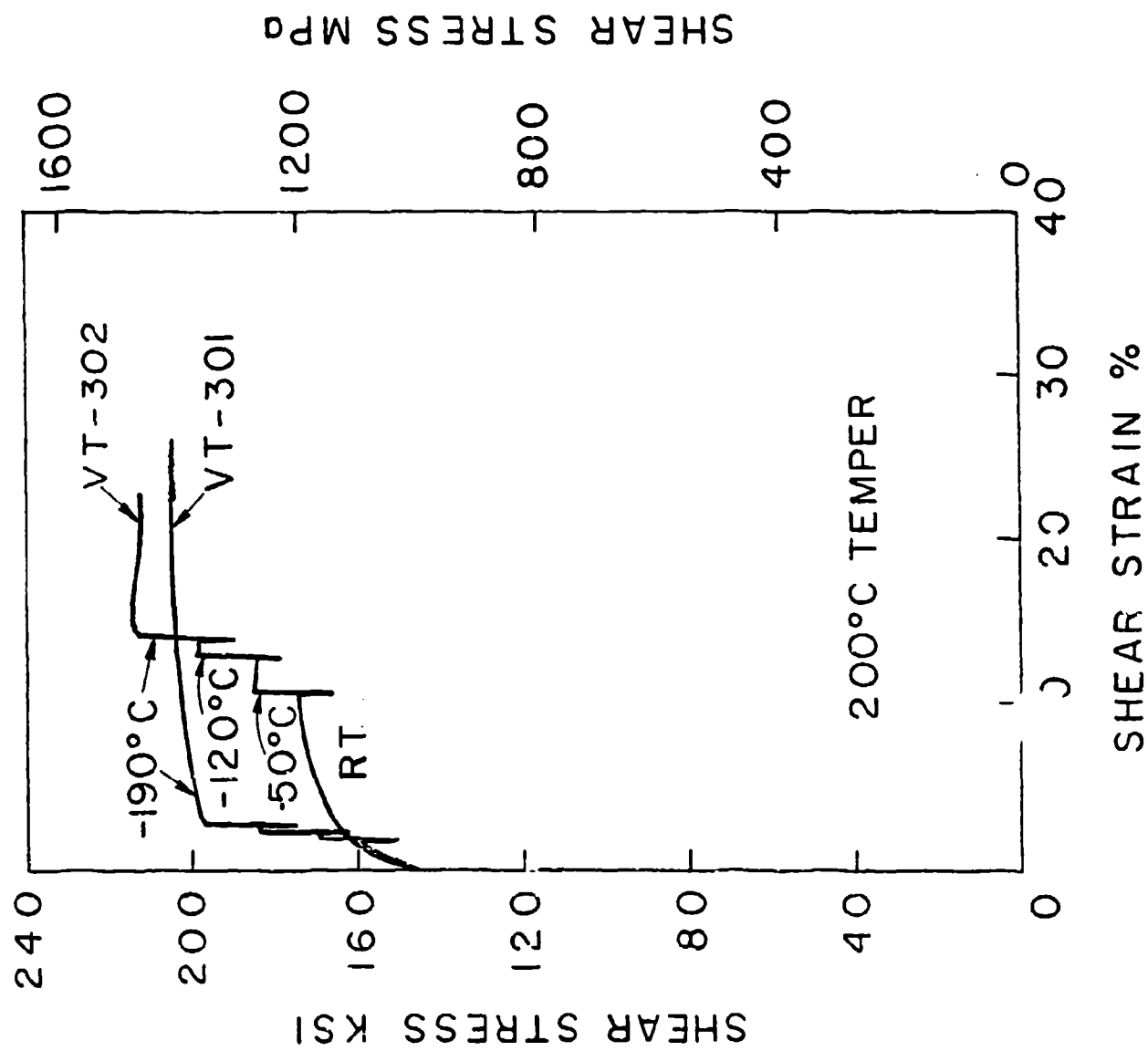


Figure 5c Multiple Incremental Temperature Tests at $\dot{\gamma} = 6 \times 10^{-4} \text{ s}^{-1}$, 200°C Temper.

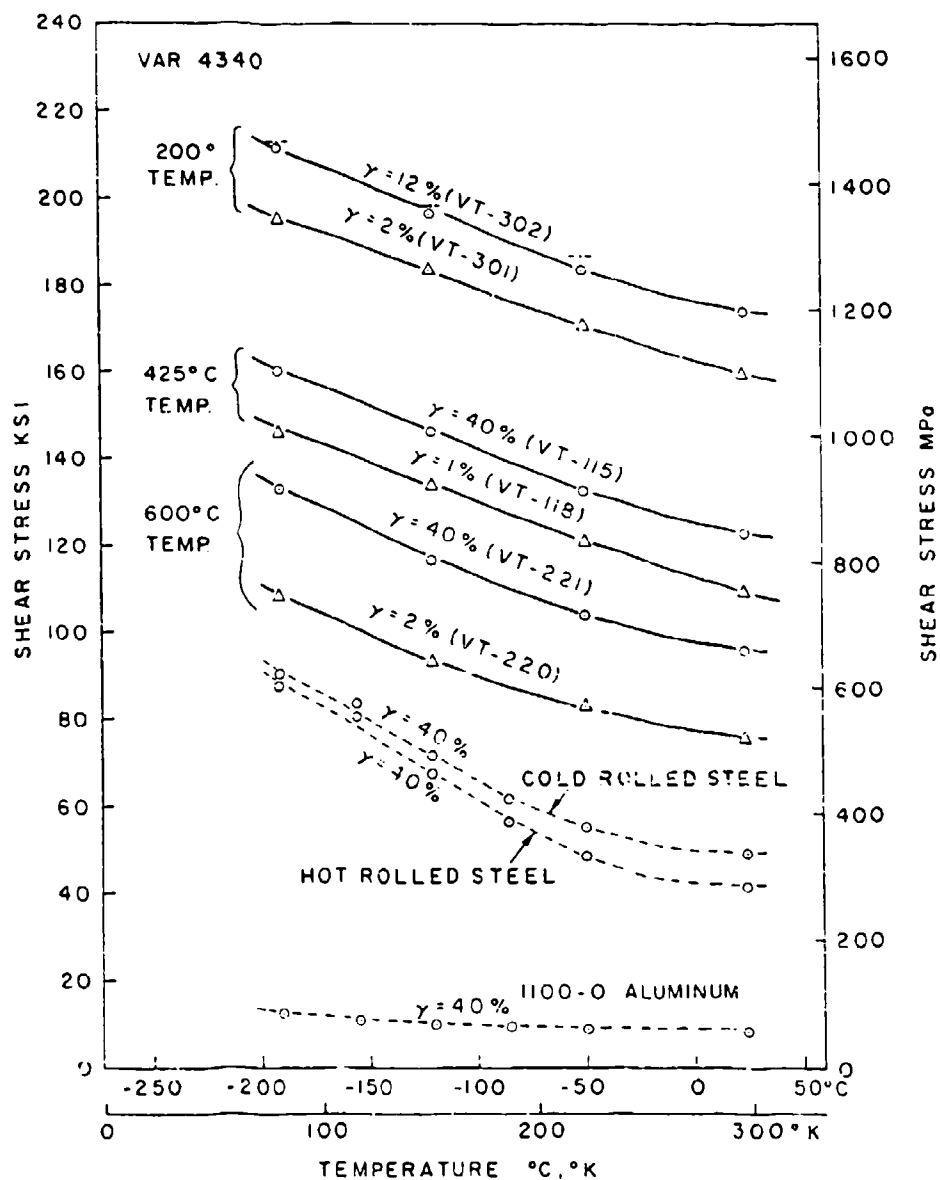


Figure 6 Results of Tests Involving Multiple Decrements in Temperature. All tests start at room temperature. The strain at which the temperature decrements occur is indicated on each curve. $\dot{\gamma} = 6 \times 10^{-4} \text{ s}^{-1}$.

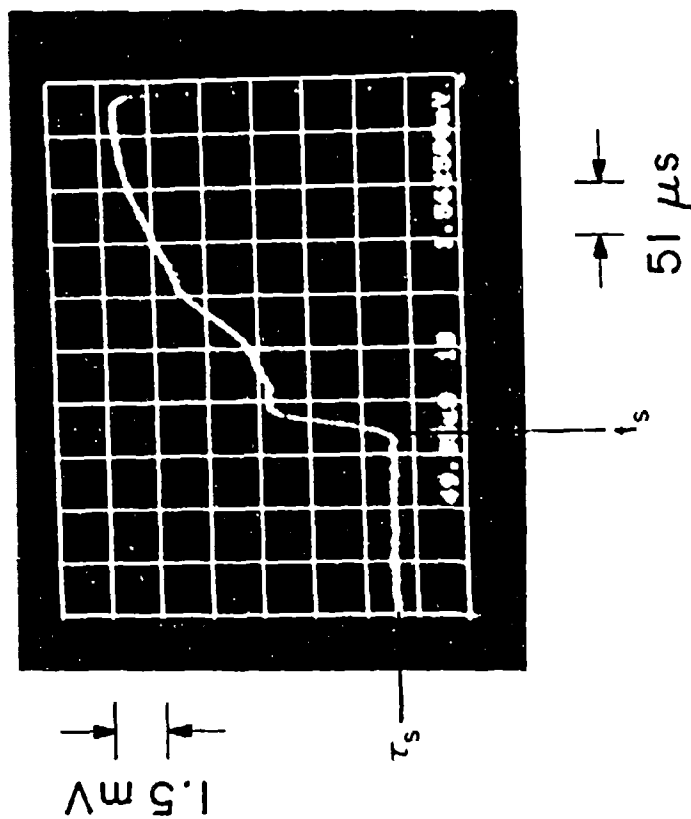


Figure 7 Oscilloscope showing the transmitted pulse in an Incremental Strain Rate Test. 200°C Temper (VT-314). Room temperature test with pre-strain of 0.5%.

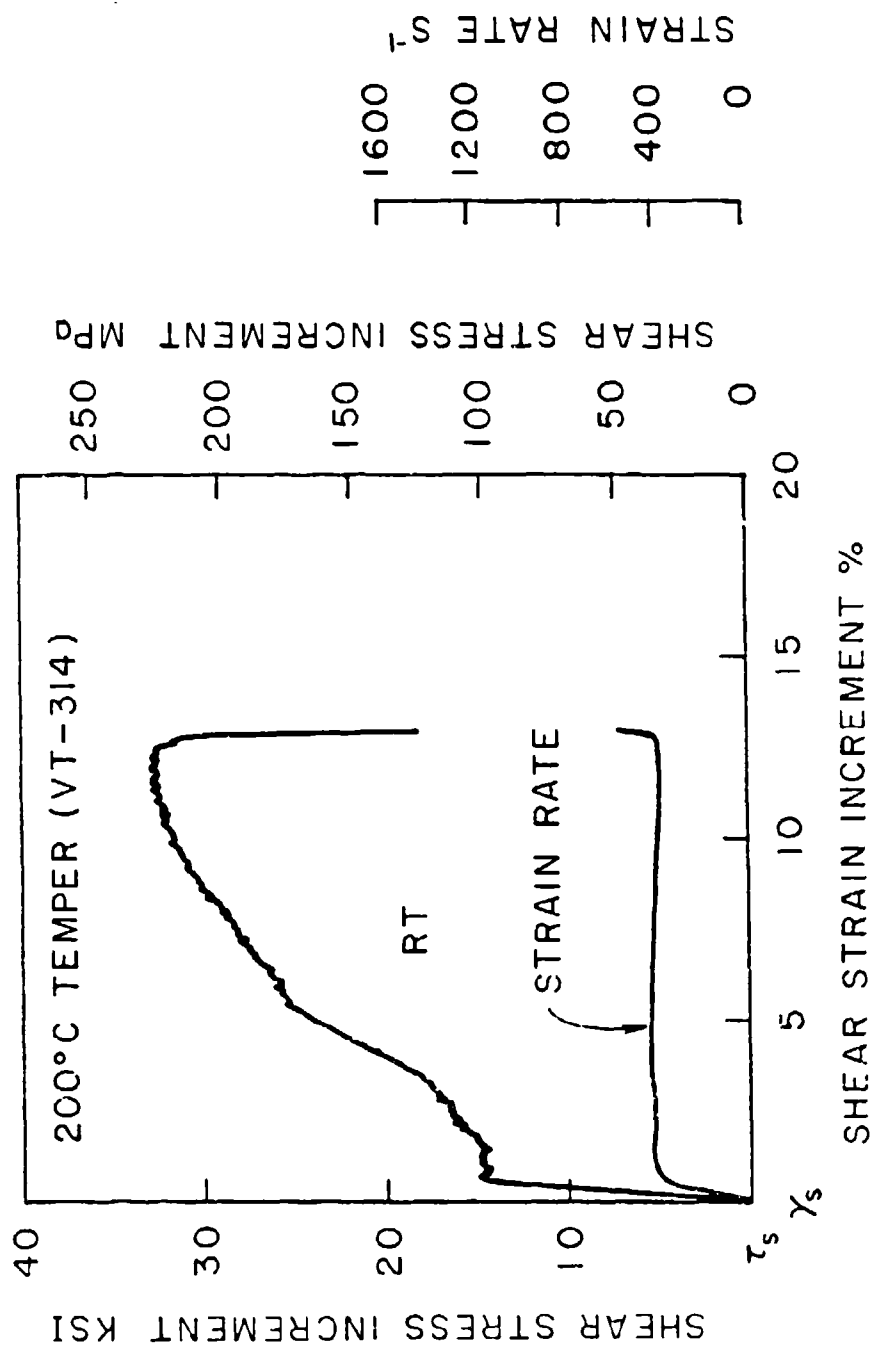


Figure 8 Stress and Strain Rate as Functions of Strain in Incremental Strain Rate Test. (VT-314). See Figure 7.

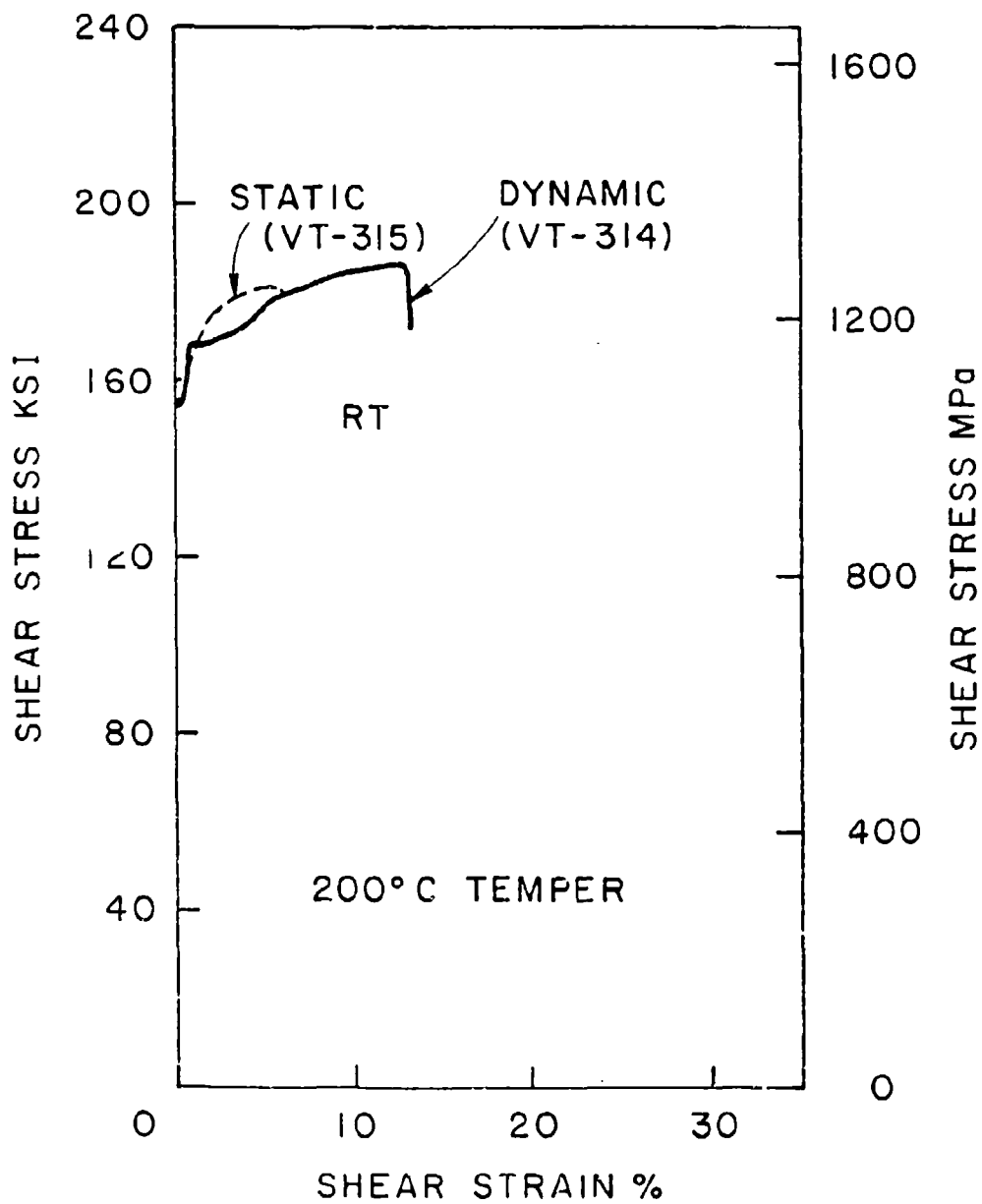


Figure 9 Quasi-Static and Dynamic Stress Strain Curves at Room Temperature, 200°C Temper.

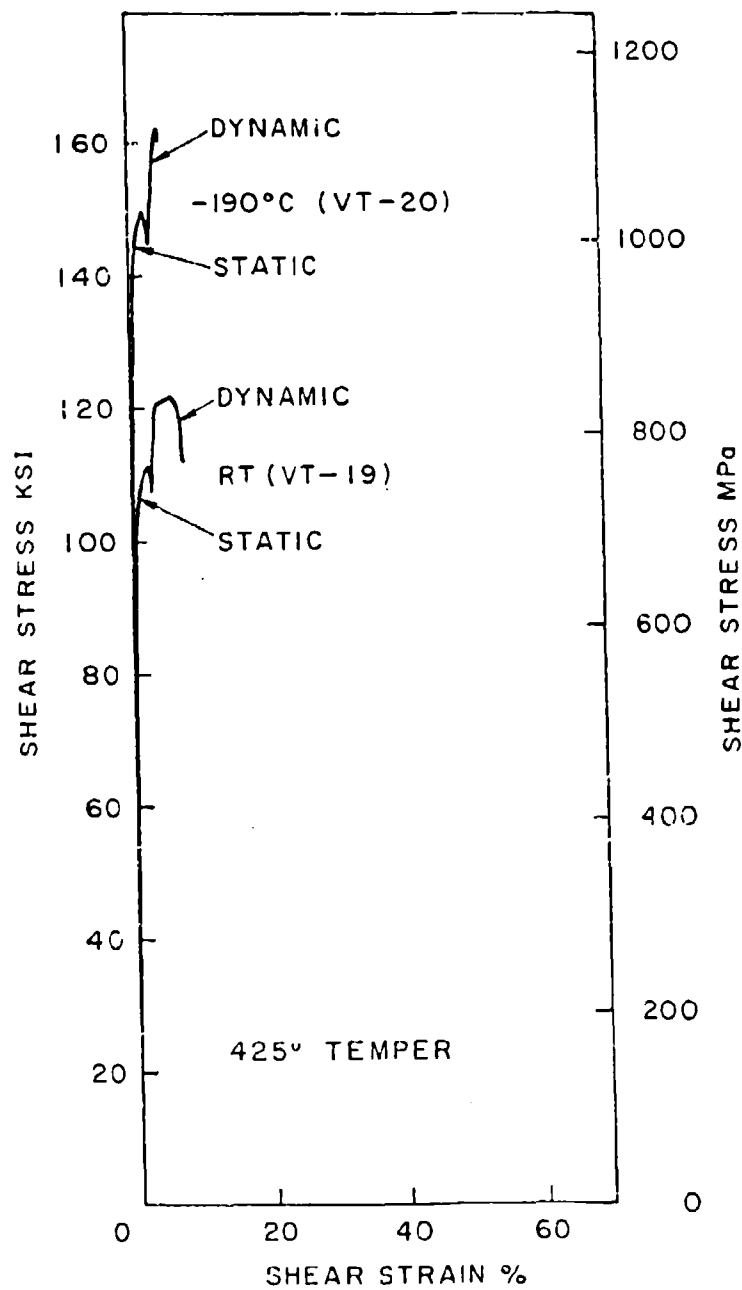


Figure 10 Incremental Strain Rate Tests, 425°C Temper. Test temperature as indicated.

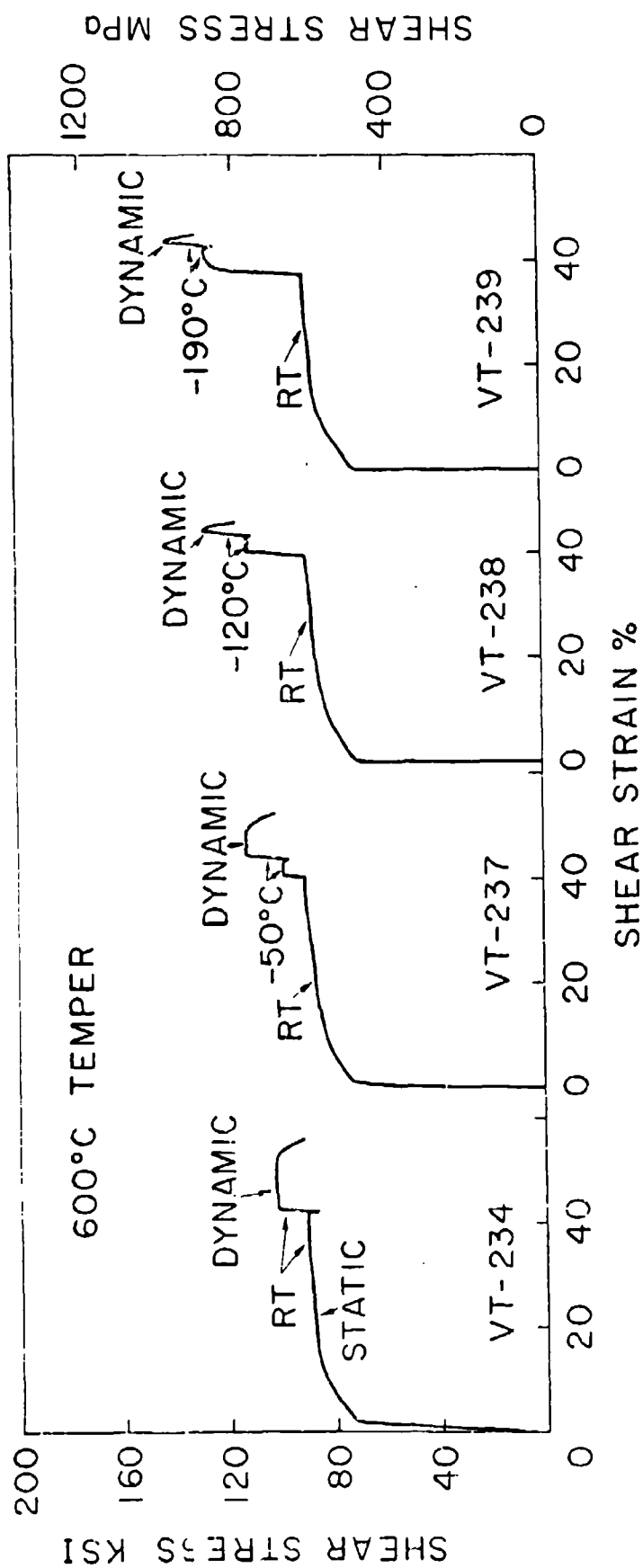


Figure 11 Combined Decremental Temperature and Incremental Strain Rate Tests.

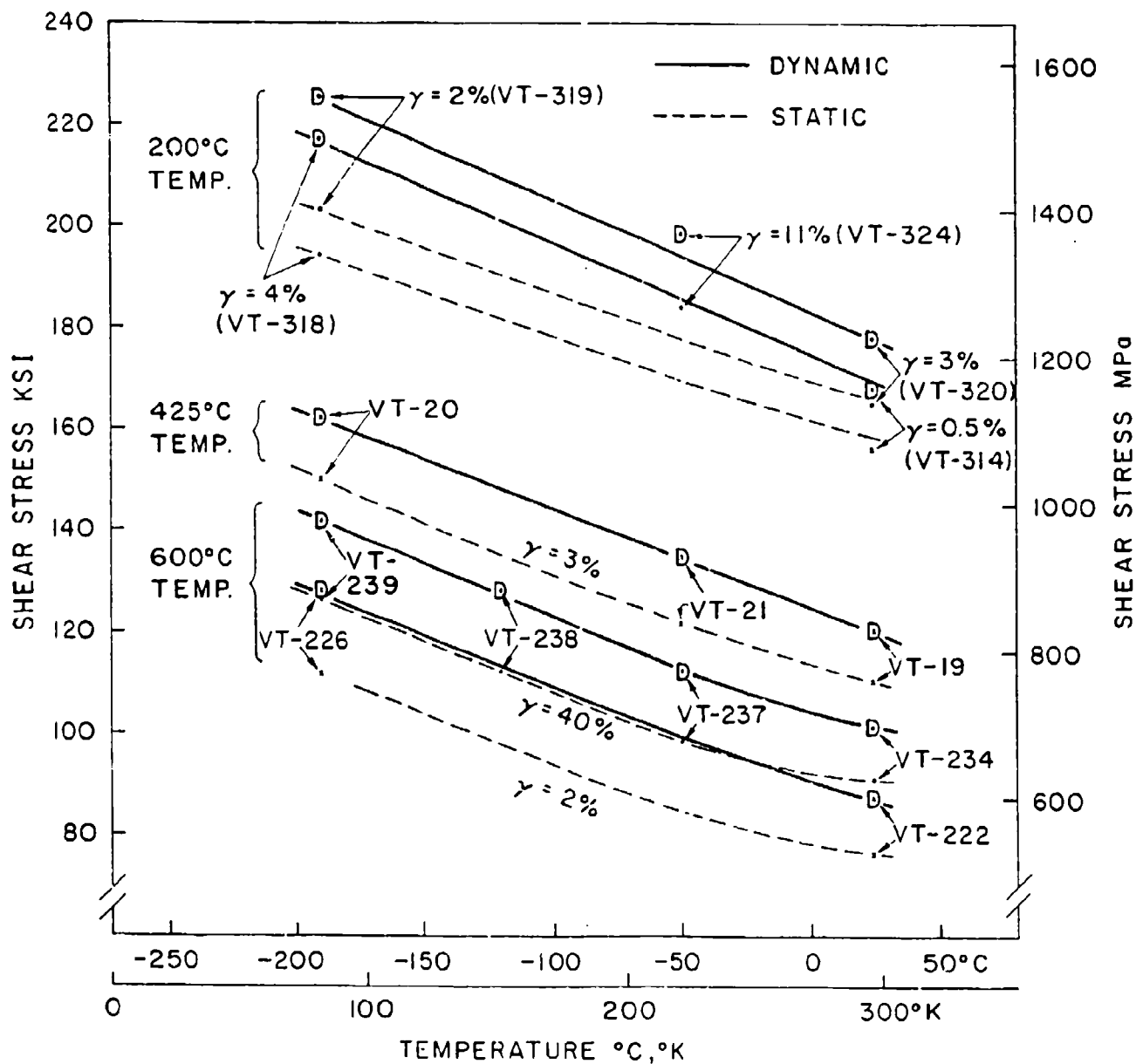


Figure 12 Results of Incremental Strain Rate Tests. Dashed lines show stress values just before increments in strain rate and solid lines just after. Increments in strain rate are imposed at strain values indicated on curves.

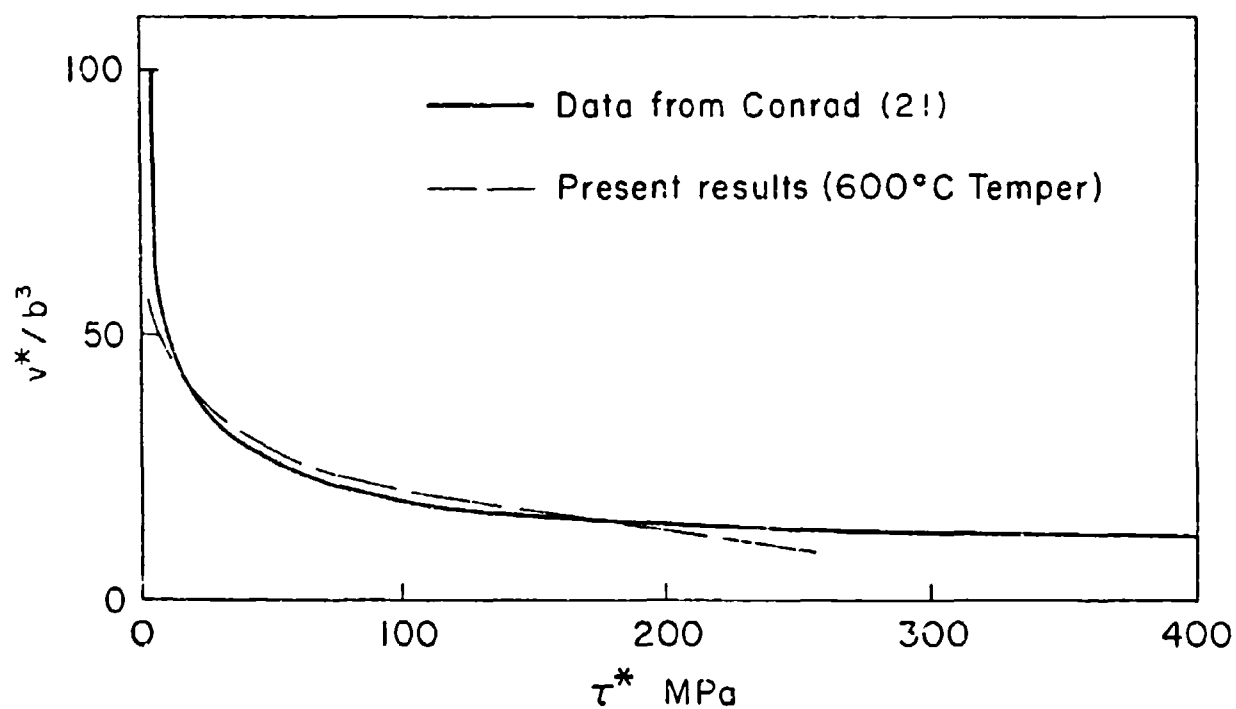


Figure 13 Activation Volume during Plastic Flow as a Function of the Thermal Stress Component. Results for AISI 4340 VAR steel tempered at 600°C are compared with average of data compiled by Conrad (21) for iron and steels.